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Hydra V: Hydrogen Experimental Dive to 450 Meters

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ABSTRACT

HYDRA V was performed in COMEX Marseille Hyperbaric Research Center in May and June 1985. During this experiment, 6 divers lived at a simulated depth of 450 meters in a hyperbaric atmosphere composed of hydrogen, helium and oxygen (Hydreliox).

Traditional deep diving with helium is limited by 2 factors :

- High Pressure Nervous Syndrome (HPNS) that causes motricity disorders beyond 300 meters.
- Gas density that impairs pulmonary ventilation.

Hydrogen should extend these limits thanks to its narcotic potency that has an antagonistic effect on the HPNS syndrome and thanks to its light molecular mass.

HYDRA V, first hydrogen experimental saturation dive, was successfully performed.

All the equipment and techniques especially developed to use hydrogen have proved entirely satisfatory.

From the biomedical standpoint, the improvement with reference to Heliox is outstanding :

- No High Pressure Nervous Syndrome,
- Easier breathing.

The very promising results of HYDRA V will hopefully lead to quick offshore industrial applications. Hydrogen will enable divers to work in water depths ranging from 400 to 600 meters and certainly beyond.

INTRODUCTION

For more than 20 years now, all deep commercial dives have been carried out using breathing mixtures made up essentially of helium and oxygen.

Illustrations at end of paper.

Helium has allowed the professional diver to work on the continental shelf area down to depths of 300 meters. In this range, equipment and methods are now relatively well established. However, in spite of its remarkable qualities, helium alone cannot be the vector of oxygen in breathing mixtures beyond a certain depth.

Indeed, deep divers must cope with 2 limiting factors:

- The High Pressure Nervous Syndrome (HPNS), linked to the effects of hydrostatic pressure on the central nervous system. These appear in the 250 / 300 meter range and increase with depth, causing motor disturbances that may seriously impair work efficiency.
- The density of breathing mixtures, which increases proportionally to pressure, demands a subsequent increase in breathing efforts, which hinders work capacity.

The following countermeasure may be proposed :

- The effects of pressure can be reduced by adding to the breathing mixture a given amount of narcotic gas (helium is not).
- Gas density can be reduced by using a vector gas that has a lower molecular mass than helium.

Hydrogen is the only gas that satisfies both these criteria. Because of the progress in the search and exploitation of deep offshore oil fields, COMEX decided to launch a new program for developing hydrogen diving. Experiments have been carried out both at sea and at its research center in Marseille.

- Hydra III - June 1983: dives at sea at depths of 75 and 91 meters.
- Hydra IV - November 1983 : chamber dives at depths of 120, 150, 180, 240 and 300 meters.
- Hydra V - May and June 1985 : chamber saturation dives at 450 meters.

The positive results of these series of experiments lead us to envision a rapid industrialization of deep diving using hydrogen breathing mixtures.

CHOICE OF AN ANTI-HPNS GAS VECTOR

Many hyperbaric experiments were performed to study HPNS and to establish various methods to reduce its effects. A significant reduction in HPNS was obtained by adding to the helium-oxygen mixture a given amount of nitrogen, the narcotic potency of which is well known.

Unfortunately, the benefit of using nitrogen to reduce HPNS is hindered by a significant drawback: increase in the breathing mixture density, because nitrogen is seven times heavier than helium.

During the JANUS IV operation, the first dive to 501 meters (world record), carried out in the Mediterranean Sea in 1977 by COMEX, a TRIMIX gas mixture was used to pressurize the chambers. The composition of the mixture was as follows :

- Oxygen = 1%
- Nitrogen = 5%
- Helium = 94%

that results in a density of 10.5 g/l.

By using Heliox at the same depth, the density would have been 8.2 g/l, i.e. 22% less.

We therefore see that a large amount of nitrogen cannot be used without hindering ventilatory function and reducing respiratory comfort.

The use of hydrogen instead of nitrogen was therefore decided upon, because it is twice as light as helium and because it is narcotic under raised pressure, as proved by previous animal experiments carried out in several laboratories.

QUANTIFICATION OF THE NARCOTIC POTENCY OF HYDROGEN

The narcotic effect of a gas species is directly related to its partial pressure. Hence, the narcotic effect of nitrogen during air diving occurs at about 50 meters in the average diver and then rapidly increases, becoming dangerous beyond 70/75 meters. The partial pressure of nitrogen at 50 meters is 4.7 bar, and 6.7 bar at 75 meters.

In order to quantify the narcotic potency of hydrogen in man, COMEX carried out in November 1983 a world premiere experiment. During this experiment, 6 Heliox-saturated divers (3 professional and 3 scientific) breathed "Hydrox" (H_2 and O_2) and "Hydreliox" (H_2, He, O_2) mixtures for several hours at depths of 120, 150, 180, 240 and 300 meters.

At 180 meters, distinctive narcosis signs were observed in some of the divers. At this depth, with a breathing mixture composed of 2% oxygen and 98% hydrogen, the hydrogen partial pressure was 18.6 bar.

At 240 meters, the narcotic effect was evident in all divers. At this depth, with the same mixture, the hydrogen partial pressure was 24.5 bar.

At 300 meters, the divers breathed Hydreliox.

Two Hydreliox mixtures were tested :

- Mixture 1 : Hydrogen = 74% (partial pressure 22.9 bar).
  Helium = 24%
  Oxygen = 2%
- Mixture 2 : Hydrogen = 59% (partial pressure 18.3 bar)
  Helium = 39%
  Oxygen = 2%

At this maximal depth we wanted to eventually check the existence of any reversal of narcosis on the premise of an antagonistic action of pressure : "pressure reversal effect" (See Figure 1).

With mixture 1 at 300 meters, the narcosis was clearly less significant than with Hydrox at 240 meters (partial pressure = 24.5 bar).

With mixture 2 at 300 meters, the signs of narcosis were no longer discernible whereas they were at 180 meters using Hydrox (partial pressure = 18.6 bar).

Thus, at 300 meters, the hydrostatic pressure seems to be sufficient to exert a small reversal effect on hydrogen narcosis. However, this phenomenon was to be confirmed and this was a major objective in the HYDRA V experiment.

OBJECTIVES OF THE HYDRA V DIVING EXPERIMENT

On account of the positive results of the HYDRA IV experiment at 300 meters, HYDRA V was designed at 450 meters with two categories of objectives in mind :

1. Technical
   - Definition of hydrogen saturation diving procedures.
   - Pre-industrialization of life support systems specific to hydrogen atmospheres.
   - Definition of safety equipment and procedures.
2. Physiological
   - Study of the anti-HPNS effect of hydrogen.
   - Verification of the pressure reversal effect.
   - Toxicological study of the effects on man of long exposures to high partial pressures of hydrogen.
   - Control of isobaric counter-diffusion upon transfer from a hydrogen atmosphere to a helium atmosphere.
   - Study of the ventilatory function at rest and during muscular exercise, both under dry and wet conditions.

EXPERIMENTAL SET-UP

The hyperbaric facilities of the COMEX Experimental Center were arranged to obtain two distinct zones (Figure 2).

1. Hydreliox zone

   The Hydreliox zone was made up of 3 interconnected spherical diving chambers, with specific arrangements for hydrogen use. The system could accomodate 3 saturated divers.

   - Sphere 1 : Living chamber, equipped with 3 bunks.

   - Sphere 2 : Sanitary chamber also equivalent to a diving bell on top of the wet pot.

   - Sphere 3 : Laboratory and work chamber under dry conditions, or wet pot for underwater studies.

   Physiological comfort was maintained by means of a new life support system, specially developed for Hydreliox atmospheres.

   This equipment ensured :

   - thermo-hygrometric control,
   - the elimination of carbon dioxide and odours,
   - the continuous re-oxygenation of the gas mixture to compensate the divers' oxygen consumption, and its elimination during decompression.

2. Heliox zone

   A high capacity cylindrical chamber with transfer lock, able to accomodate up to 8 persons (6 divers + 1 doctor with his assistant, if required in a Heliox atmosphere). This chamber was connected to Sphere 2 of the Hydreliox zone. It provided a retreat position in the event of an emergency and furthermore was intended for the final decompression of the divers.

   It was connected to a conventional life support system for maintaining comfortable physiological conditions.

   This chamber housed scientific equipment identical to that in Sphere 3 to carry out reference tests in the helium zone under the same pressure conditions as in the Hydreliox zone.

SAFETY

The flammability limits of hydrogen at atmospheric pressure are the following :

	Low limit	High limit
In air	4 %	74.5%
In oxygen	4 %	94 %

Prior to the HYDRA IV experiment, we determined flammability limits of (H_2, H_e, O_2) ternary mixtures under pressure.

Results can be summarized as follows :

1. Hydreliox mixtures are non flammable when the oxygen fractional concentration is lower than 4.4% until a total pressure of 76 bar, i.e. a pressure equivalent to a depth of 750 meters (Figure 3).
   It can therefore be stated that there is no longer a risk of fire in a hyperbaric chamber as soon as the oxygen concentration is lower than 4.4%, corresponding to the following partial pressures as a function of depth :

PO_2 (mbar)	Depth (meters)
400	81
500	114
600	126

   To have a wide safety margin, we decided to inject hydrogen into the chambers only from 200 meters, where, for an oxygen pressure of 400 mbar, the oxygen fractional concentration is lower than 2%.
2. Furthermore, this Hydreliox mixture is flammable only with a hydrogen fractional concentration higher than 7.5 for a total pressure of 10 bar (Figure 4). During decompression, hydrogen is selectively eliminated to ensure a concentration lower than 4% when reaching 200 meters.

It can therefore be stated that the fire risk is almost non-existent at great depth in hydrogen atmospheres.

On the other hand, the fire risk outside the chambers, eventually induced by leaks must be seriously taken into consideration.

All gas circuit hose pipes were replaced by rigid stainless steel or copper pipes. The chambers of the hydrogen zone were covered by a hood connected outdoors through a high flow capacity gas exhaust system. A set of hydrogen detectors triggered the rates of functioning of the exhaust system with respect to two alarm thresholds:

0.15% hydrogen – Extraction rate n° 1 = 20,000 m^3/h
0.5 % hydrogen – Extraction rate n° 2 = 40,000 m^3/h

The 40,000 m^3/h extraction rate slightly depressurizes the experimental Center.

Thus, the slightest leak could be immediately diluted and drawn out of the building.

HYDRA V EXPERIMENTAL DIVE AT 450 METERS

The HYDRA V experimental dive at 450 meters was carried out from May 3rd to June 7th, 1985, at COMEX's Hyperbaric Center in Marseille (the dive profile is given in Figure 5).

9 divers had been preselected to provide 2 teams of 3 divers :

Team A :	Patrick RAUDE	– COMEX
	Louis SCHNEIDER	– COMEX
	Jean-Guy MARCEL AUDA	– French Navy
Team B :	Yves LANGOUET	– COMEX
	Jean-Pierre MACCHI	– Institut National de Plongée Professionnelle
	Serge ICART	– French Navy
Substitutes :	Roger OUZENANE	– COMEX
	Alain MARCHENAY	– French Navy
	Jean-Maurice AUTHIE	– French Navy

The COMEX research team was assisted by the following specialized laboratories :

- Centre National de Recherche Scientifique (CNRS) :
  Respiratory neurology and physiology underwater.
- Centre d'Etude et de Recherche de Biophysiologie du Service de Santé des Armées (CERB) – French Army :
  Cardio-respiratory physiology – dry atmosphere Biology and psychometry.
- Commission d'Etudes Pratiques d'Intervention Sous la Mer (CEPISMER) – French Navy :
  Hyperbaric medecine
- Groupe d'Intervention Sous la Mer (GISMER) – French Navy :
  Diving procedures.
- Centre d'Etude et de Recherche des Techniques Sous-Marines de la Direction des Chantiers et Armes Navales (CERTSM – DCAN) :
  Decompression – Doppler control
- Optimisation des Conditions de Travail et Application de la Recherche en Ergonomie et Securité (OCTARES) :
  Psychometry.
- Centre d'Ophtalmologie de Martigues (CMO) :
  Ophtalmology.
- Naval Medical Research Institute (NMRI) of U.S. Navy :
  Exploration of cardio-respiratory functions.
- Swedish Defense Research Institute – Naval Medecine Division of Swedish Navy (SDRI – NMD) :
  Psychometry.

GENERAL PROGRESS OF THE EXPERIMENT

1. Confinement :
   Team A : from May 3rd to 7th, 1985
   Team B : from May 7th to 11th, 1985

   The divers were exposed to Heliox at 10 meters for baseline cardiological and neurological measurements.

2. Compression :
   Team A : from May 7th to 9th, 1985
   Team B : from May 13th to 14th, 1985

   Total duration : 38 hours with 2.5 hour stops at 100, 200, 300 and 400 meters.

   Up to 200 meters : Compression with helium

   From 200 to 450 meters: Compressionwith hydrogen

   At 450 meters the Hydreliox mixture has the following composition :

	Fractional Concentration	Partial Pressure
Oxygen	0.0087	0.4 bar
Helium	0.4478	20.6 bar
Hydrogen	0.5435	25 bar

   The average density of this dry mixture at 37° C was 5.5 g/liter with a reduction of 26% compared to a Heliox mixture ($H_e - O_2$) and of more than 50 % compared to a Trimix mixture (H_e, N_2, O_2) .

3. Stay on the bottom

   Team A :

   - From May 9th to 10th, 1985 : under Hydreliox, with physiological, psychometrical, biological and medical tests under dry conditions.

   - May 11th, 1985 : Transfer to the helium chamber after an intermediate stay of 8 hours under a hydrogen partial pressure of 12.5 bar.

     On arrival in the helium chamber, sudden occurrence of HPNS, and recovery within 24 hours.
     Evidence of isobaric counter-diffusion circulating bubbles, suppressed by a 20 meter therapeutical recompression.

   - May 12th, 1984 : Decompression to 450 meters.

   - From May 14th to 15th, 1985 : Reference tests in Heliox at 450 meters.

Team B :

- From May 14th to 17th, 1985 : with physiological, psychometrical, biological and medical tests under dry conditions.
- From May 18th to 19th, 1985 : Test of work performance underwater with cardio-respiratory measurements.

4. Decompression :

Team A :
- May 17th, 1985 : Start of decompression with Heliox.
- May 31st, 1985 : End of decompression

Team B :
- May 19th, 1985 : Start of decompression with Hydreliox.
- May 31st, 1985 : Transfer to Heliox at 157 meters. Decompression continued
- June 7th, 1985 : End of decompression.

RESULTS

1. Technical :

No significant technical incident was observed during the experiment and the entire technical set-up proved to be perfectly adapted to this new method of diving.

- Special life support system for hydrox atmospheres :

The system was capable of controlling the environmental conditions inside the chambers at the precise values demanded for physiological comfort, with remarkable accuracy and reliability.

- Automatic oxygen make-up :

The safety device designed to limit the oxygen admission in case of malfunction of the oxygen make-up system, was never triggered, both during compression and decompression where the oxygen requirement is however very significant.

- Safety equipment :

The multi-detector equipment employed played its part correctly. A leak occurred and was quickly detected and controlled in complete safety.

- Operating procedures for the saturation diving facilities :

These procedures had been defined so that at any time, under any circumstances and at any location of the diving system and its associated facilities, there was no possibility of obtaining a flammable mixture.

No incident having been observed, we can say that the procedures were well adapted to this new diving technique and correctly applied by technical personnel.

2. Biomedical :

Placed under permanent medical supervision, including frequent blood tests, electro-encephalographical monitoring and work performance tests, the HYDRA V experiment clearly demonstrated the benefits of hydrogen mixtures in very deep diving.

- Toxicology :

The long exposure at 45 bar at a hydrogen partial pressure of 25 bar proved to be harmless. Blood analysis data (chemical, enzymological and histological) were not significantly changed either during the experiment or during the weeks that followed.

- Anti-HPNS effect :

HPNS which usually appears in the 300 meter range in the case of Heliox was not evidenced up to 450 meters in any of the 6 divers with Hydreliox.

None of the well-known symptoms related to HPNS were observed: neither tremor, nor dysmetria, nor the characteristic lack of relaxation, and febrility, that eventually announce forthcoming myoclonias.

Normal through the nose breathing and subsequently no dysphagia, no loss of appetite and insignificant loss of weight.

Another remarkable fact, the total absence of NJJS (no joint juice syndrome).
This condition contrasted so much with that the divers had previously experienced during other deep saturation dives carried out either with Heliox or Trimix - Nitrogen, that, despite the stress due to confinement, general good humor was the constant feature during the stay in Hydreliox.

- Isobaric counter-diffusion :

In spite of the precautions taken, we were amazed by its intensity at the end of the Hydreliox to Hydrox switch in the A team only. Doppler detection simultaneously evidenced circulating bubbles. The 20 meter therapeutic recompression stopped this phenomenon and enabled a normal situation to be regained.

- Transfer methods from a Hydreliox mixture to Heliox :
The isobaric transfer from a high hydrogen pressure to an equal pressure of helium needs much time to be carried out under safe conditions. This eliminates any diving procedure involving rapid transfers because of the risk induced by counter-diffusion phenomena.

- Respiratory comfort :
The respiratory tests gave results which corresponded to what was expected. Physiological data seemed to indicate that the divers never approached a ventilatory limit. This confirmed the breathing comfort provided by Hydreliox mixtures. The respiratory equivalent of oxygen remained relatively high, and carbon dioxide retention was never observed.

CONCLUSIONS

The HYDRA V experiment, first hydrogen saturation dive ever completed, allowed us to answer several questions.

1. The anti-HPNS effect of hydrogen was evidenced, as predicted from theoretical considerations. During their stay in Hydreliox at 450 meters, the divers subjectively felt as well as during a saturation dive in Heliox at 200 meters where they are never affected by this syndrome.
   They also noticed a respiratory comfort and ease of effort that made some of them really enthusiastic to use this new gas mixture.

2. Absence of any toxicity was confirmed by all biological tests carried out throughout the experiment and during the weeks that followed. Hydrogen seemed to behave as an inert gas in breathing mixtures. Nevertheless, toxicological investigations should be continued to confirm the total harmlessness during prolonged Hydreliox exposures.

3. Isobaric counter-diffusion, may cause problems at great depths during transfer from hydrogen to helium, if one wants to use a "mixed diving method", with Heliox saturation and Hydreliox bell diving. Merely an "all hydrogen" method seems to be recommended, according to procedures similar to those used for the second diver team during HYDRA V.

With this experiment, we have proved that heavy saturation diving equipment, initially intended for helium, can be adapted to hydrogen and offers all safety guarantees. Modifications are required only for associated sub-systems and do not ask for prohibitive costs.

Within the limits of the depth range of these experiments, the positive results already obtained in the HYDRA program, open the gateway to the pre-industrialization of this new method of diving.

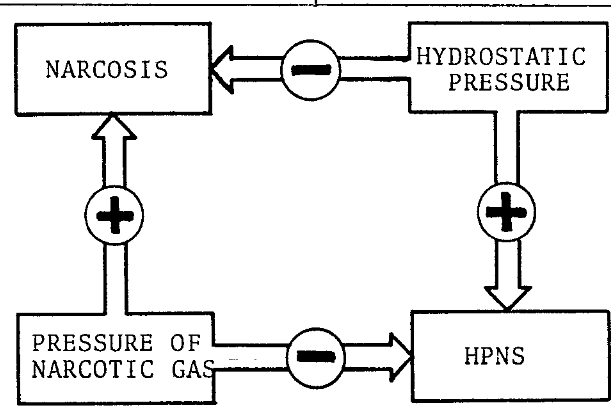

Figure 1 : HPNS AND NARCOSIS INTERACTIONS

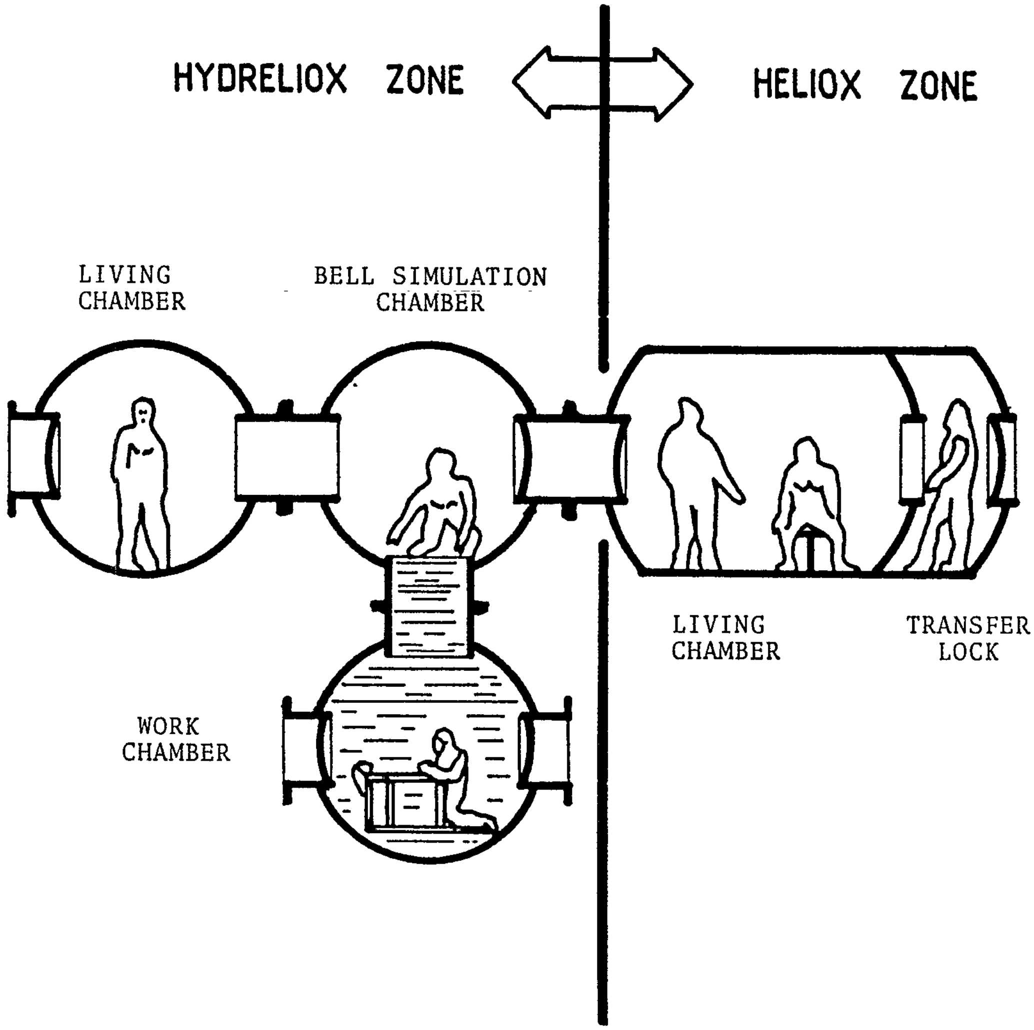

Figure 2 : HYPERBARIC CHAMBER COMPLEX

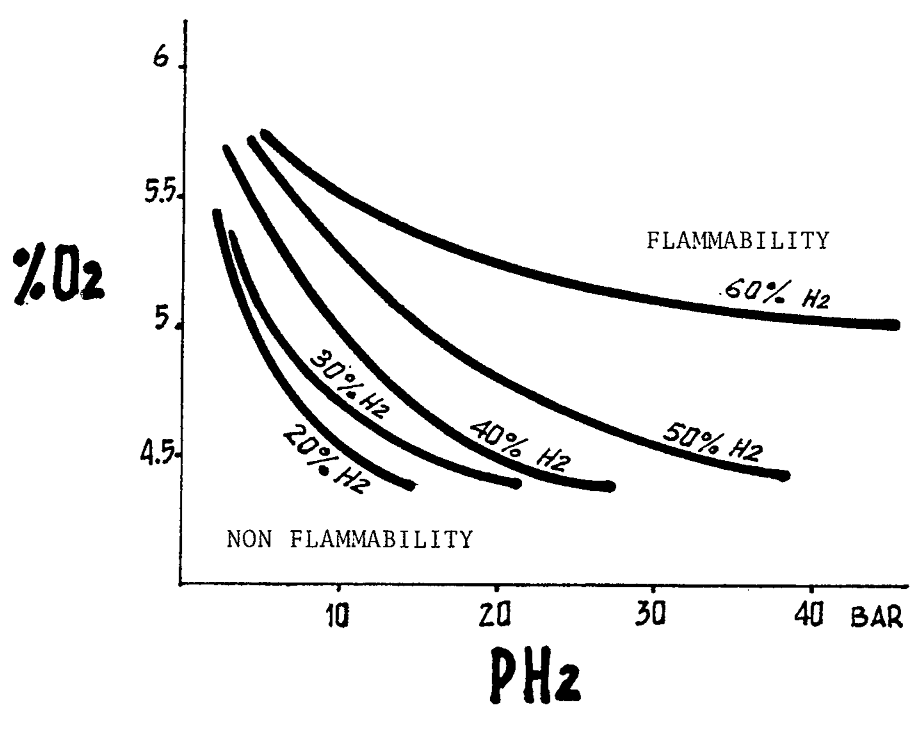

Figure 3 : FLAMMABILITY OF HYDRELIOX MIXTURES

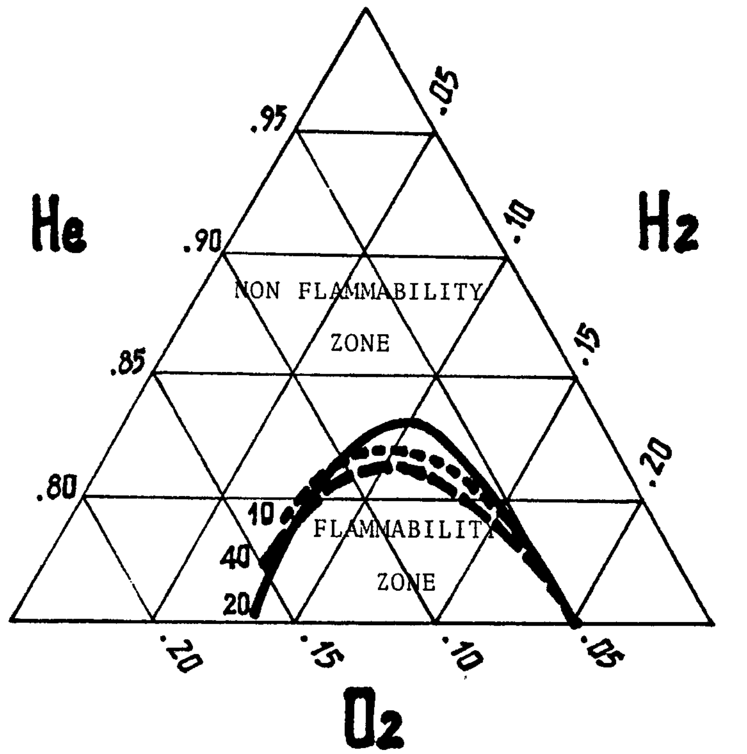

Figure 4 : LOW FLAMMABILITY LIMITS OF HYDRELIOX MIXTURES at 10, 20 and 40 BAR.

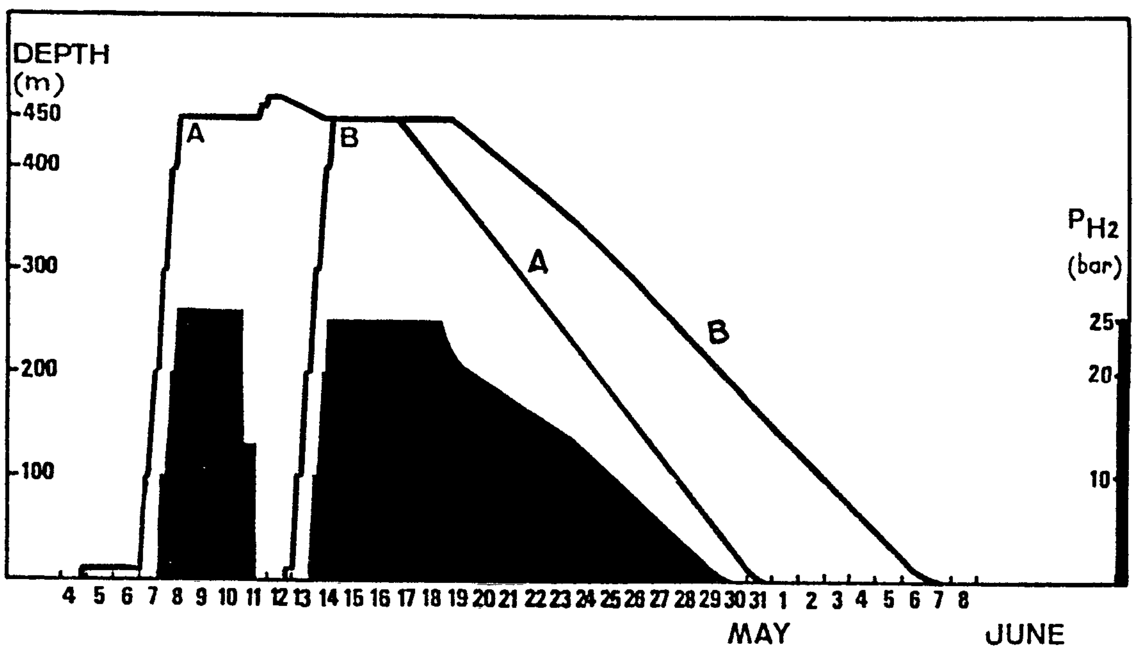

Figure 5 : HYDRA V DIVE PROFILE